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THE STRENGTH OF THE EARTH'S CRUST

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PART V. THE DEPTH OF MASSES PRODUCING GRAVITY ANOMALIES AND DEFLECTION RESIDUALS

SECTION B

APPLICATIONS OF CRITERIA TO DETERMINE THE LIMITS OF DEPTH, FORM, AND MASS

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DEPTHS INDICATED BY THE MAP OF DEFLECTION RESIDUALS

General relations shown by deflections.—Hayford gives a plate¹ which shows all the residuals of Solution H. These are laid off as arrows and show graphically the magnitude and direction of the portions of the deflections which are outstanding after allowance is made for the deflections calculated according to Solution H. They therefore show the excesses or deficiencies of mass in the crust

¹ *Supplementary Paper*, illustration No. 3; also Bowie, 1912, illustration No. 5.

as measured against the demands of the hypotheses made in that solution. In Fig. 12A is reproduced a portion of Hayford's chart. A general inspection of the map of the residuals of Solution H shows that many of the large deflections of opposite sign lie comparatively close together. On a line connecting two stations, Fx is the component of the deflection which lies in that line, Fy is the component at right angles to that line. In most cases not enough stations are located on an approximately straight line to permit well-defined curves to be drawn for Fx and Fy . But it has been shown that for spheres and other concentrated masses the curve for Fx rises steeply from zero to maximum value and sinks away more gently beyond. Even for flat disks the outer part of the deflection curve will be flatter than for the inner part. Random locations on the curve are therefore more likely to give the maximum measurement at some point beyond the real maximum rather than at some point between the epicenter and the real maximum. Using these stations giving maxima for Fx as if they were at the points of real maxima will therefore give on the average too great a distance from the center to the point of real maximum Fx and consequently too great a depth to the centers of attraction. Interpreting the disturbing masses as spheres is also an assumption likely to give too great a depth, as is indicated later. Minor centers of outstanding mass will affect the positions of the points of maximum value, but in a sufficient number of examples this effect will largely cancel out. The tabulation of the distances measured from Hayford's map between ten pairs of notable Fx maxima is given in Table XXVII.

It is seen that the distance between these maxima is more largely dependent upon the length of the sides of the geodetic triangles than upon the depth to center of mass, since in less than half of these illustrations did a station fall between the two maxima. The distance between the real maxima is then probably somewhat greater than 86 km., the average of the six distances without intervening stations, but is probably somewhat under the general mean of 110 km. This mean distance of 110 km. between ten notable maxima of Fx corresponds to a mean depth of spheres of 79 km. Considering the various assumptions made, it is seen that

the mean depth of masses producing these deflections is probably much less than 79 km. They belong, therefore, to the outer half of the zone of compensation.

TABLE XXVII

DISTANCES BETWEEN ADJACENT LARGE DEFLECTIONS OF OPPOSITE SIGN

Locality of Mass	Sign of Mass	Numbers of Stations	Stations between	Distances between in Km.
New Jersey	+	255-142	0	110
Kentucky-Ohio	+	85-84	0	100
Georgia-Florida	+	292-294	1	160
Florida	+	299-300	0	145
Michigan-Indiana	+	344-346	1	165
Illinois	+	75-74	0	90
Nebraska	+	327-329	1	170
Colorado	-	59-57	1	100
California	-	238-236	0	50
California	-	245-246	0	22
			Mean	110

There are other areas, however, as in the Adirondacks, Maine, Michigan, and the Great Basin, where the distance between the large deflections of opposite sign is considerably greater. So far as this relation goes they could be due either to broad outstanding masses in the zone of compensation or to much greater but more concentrated masses in the nucleus beneath. But the general relations to the magnitude and location of the gravity anomalies as discussed later under that subject suggest that in so far as the evidence is determinative these broader areas are also due to broad excesses or deficiencies in the outer crust, not to masses in the centrosphere. The data are not, however, in all areas of a sufficiently complete nature to give determinate solutions. In other areas, however, detailed study following the lines of criteria previously developed can bring out very definite results in regard to the location and depth of masses in spite of the interference of the fields of force from various centers. An example of what may be done by a detailed examination is shown under the next topic.

Detailed study of the Texas-Kansas region.—Fig. 12A shows the deflections as given on a north-south line of triangulation 1,000 km. in length. The gravity anomalies are shown for distances of 200 km. on each side of the traverse. The stations are sufficient in

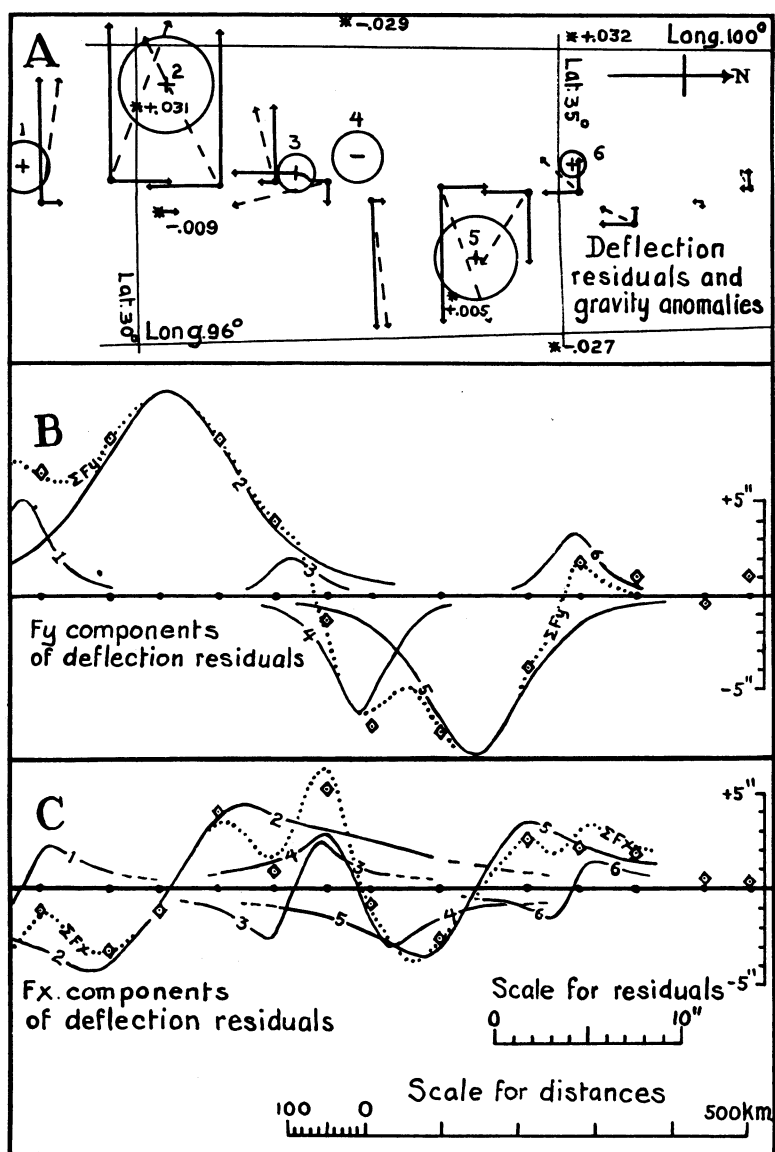


FIG. 12.—Residuals of Solution H and gravity anomalies in Texas, Oklahoma, and Kansas, with the interpretation of the outstanding masses in terms of equivalent spheres.

number and sufficiently close to a straight line to permit the application of the principles previously discussed.

The residuals are given in the north-south and east-west directions. The broken lines give the resultants. Their convergence indicates that there are two large and controlling positive masses marked on the map as 2 and 5. To account for the local variations shown by the resultants from station to station it is necessary, however, to locate smaller masses of positive or negative nature approximately as shown at 1, 3, 4, and 6. There must be of course many other centers of moderate disturbance within the area of 400,000 km. which is shown, but such as exist are far enough from the line of section not to exert an appreciable influence. It is noteworthy that gravity stations only 200 km. from the line of the traverse can show anomalies as large as -0.029 , $+0.032$, and -0.027 dyne without the masses which give these anomalies showing appreciable control over the deflections on the line of traverse. Their areas of influence are therefore restricted. The limited influence of these masses giving anomalies somewhat above the average and at a moderate distance, and the small masses locally modifying the deflections both serve to show the importance of nearness of location. This limitation of control over the deflections, restricted to distances of less than 100 to 200 km., is itself an indication that these outstanding masses lie within the zone of compensation, otherwise their effects would be more far-reaching.

The residuals permit, however, a much more detailed solution to be made. As a first approximation assume the outstanding masses to be spheres. Figs. 12B and 12C. show the results. This is not merely an arbitrary adjustment of curves and one of a number which might be devised. On the contrary, it has been shown in the discussion of Section A and especially in Fig. 11 that the ratio of the two maxima of the deflection components, F_y and F_x , and the ratio of EE' to $E'M$ hold a definite relation to the distance and depth of the center of the sphere. Therefore if curve 2 be drawn in proper proportion and as shown in B in order to satisfy the demands of the y component, then the maximum value of F_x must not be over 40 per cent of the maximum value for F_y , even if the center

of mass is close to the surface. It may be any value less than 40 per cent of maximum Fy , according to the depth of the center. But having chosen that ratio which appears to fit the demands of the data, the distance of the point of maximum Fx from the point of zero value becomes also fixed. The curves numbered 2 in Figs. 12B and C must therefore satisfy between them the demands of the ratios shown in Figs. 11E and F. The value of EE' as deduced from either curve must be the same.

The sum of all the Fy curves in 12B is marked ΣFy and must pass through, or close to, the points which measure the values given by the deflection residuals. These points are shown as small rectangles in B and C and give ordinates which correspond with the size of the components of the residuals as shown in A. In drawing B and C the adjustment of the curves to give the proper values to ΣFy and ΣFx resulted in a slight readjustment of the centers of mass as shown in A. The positions as shown in Fig. 12A have been determined from the curves below, and their approximate agreement with the initial indications of the resultants is a check on the validity of the solution. It is seen that the epicenter of a mass should not lie on the exact intersection of any two resultants, since at the point of measurement several masses have an appreciable influence upon the direction of the resultant. The adjustment of the curves is therefore the best way of determining finally the best location of the epicenters.

The measurement of these curves gives the tabulation of data shown in Table XXVIII.

The depth to the centers of the equivalent spheres having been solved by means of the ratios given in Figs. 11E and 11F, the masses of these spheres are ascertained as follows. In Fig. 11 the value of the maximum deflections for Fy and Fx due to the unit sphere are shown for various distances of the section line from the epicenter. For example, for $EE' = 1.5D$, max. Fy is $4.6''$. Now for sphere No. 4, Fig. 12A, $EE' = 1.5D_4$ and the max. Fy is $6.2''$. But D for the unit sphere is 64 km. whereas D_4 is 31 km. Now the magnitude of the deflections for points similarly situated in two fields of gravitative force will vary directly as the respective masses and inversely with the squares of the distances. This may be put into

a formula as follows: Let there be two masses M and M_n with centers at depths D and D_n , below a horizontal plane. For points on the plane similarly situated with respect to their respective centers let the components of the deflection force be Fy and Fx for the one, Fy_n and Fx_n for the other. Then

$$M_n = \frac{Fy_n D_n^2}{Fy D^2} M; \text{ also } M_n = \frac{Fx_n D_n^2}{Fx D^2} M$$

The results of the application of this formula are shown in the last column of Table XXVIII. They have been carried out to two significant figures, but the second is not to be regarded as accurate,

TABLE XXVIII
INTERPRETATION OF RESIDUALS IN TERMS OF EQUIVALENT SPHERES

DATA								RESULTS	
NO. OF SPHERE	FROM FIG. 12			FIG. 11F	FROM FIG. 12			DEPTH IN KM.	Mass in Terms of Unit Sphere Whose $R=50$ km. $d=0.1$.
	Max. Fy	Max. Fx	Max. $\frac{Fy}{Fx}$	EE' in Terms of D	EE'	$E'M$	EE' in Terms of D		
1.....	5.1	2.3	2.20	1.7D ₁	42	35	1.20	25	+0.20M
2.....	10.8	4.4	2.46	3.0D ₂	125	95	1.31	40 to 50	+2.5 to 2.9M
3.....	2.0	2.5	0.80	0.3D ₃	13	33	0.40	43	+0.17M
4.....	6.2	2.9	2.13	1.5D ₄	47	40	1.17	31	-0.32M
5.....	8.4	3.5	2.40	2.5D ₅	88	67	1.31	35	+1.10M
6.....	3.3	1.4	2.35	2.2D ₆	34	27	1.27	16	+0.07M

even if the original data are accurate to the second place. This is because the error of the square of a quantity is approximately twice as great as the original error, and for values EE' above 1.0D the error in even the first power of D is appreciably greater than the error in the measured quantities. This of course is a consideration of the error in the determination of the depth and mass of the hypothetical spheres, not a consideration of the errors in the deflections themselves, nor related to the fact that the masses are in reality not spheres.

It has been shown previously that the interpretation of the outstanding masses in terms of spheres will give depths too great unless the real masses have their greatest dimension vertical. For the same reasons the hypothetical spheres will be of greater mass

than the real horizontally extended bodies in order to produce the same deflections as those observed.

The question arises then as to the real form and mass of the bodies interpreted here as spheres. The supplemental data at hand yield evidence only in regard to No. 2. This, however, is the greatest of the six outstanding masses in this series. The supplemental data consist of observations on gravity anomalies at three localities whose distances from the epicenter of No. 2 are as follows:

RELATIONS OF GRAVITY ANOMALIES TO THE EPICENTER OF MASS NO. 2

<i>a</i> , 47 km. S. E.	+0.031
<i>b</i> , 163 km. E.	-0.009
<i>c</i> , 250 km. N.N.W.	-0.029

Now the curves for Fv and also for the Fy component of Fh show with increasing distance from the epicenter a rapid fall from the maximum value. These effects of the gravitative force due to outstanding masses are consequently markedly local and the nature of the mass No. 2 must have a distribution such as to account for the anomaly of +0.031 at 47 km. from the epicenter. The interpretation must not give a form which will exert marked influence upon those points distant 163 and 250 km. The dominating influence of mass No. 2 on the value of Fv appears therefore to be confined to distances within 125 or 150 km. of the epicenter. But the two limiting spheres of mass $2.5M$ and $2.9M$ respectively give the relations shown in the first two lines of Table XXIX.

TABLE XXIX
INTERPRETATION OF MASS NO. 2

Form	Mass in Terms of Unit Sphere	Depth to Center in Km.	Radius in Km.	Height in Km.	Excess Density Above Mean	Fv at Epi- center in Dynes	Fv at 47 Km. in Dynes
A. Sphere.....	2.5	40	40	80	0.5	0.542	0.148
B. Sphere.....	2.9	50	50	100	0.3	0.405	0.157
C. Cylinder....	2.5	40	200	10.4	0.1	0.035	
D. Cylinder....	0.6	20	100	5.2	0.2	0.035	

The interpretation of the deflections as due to spheres gives a gravity anomaly at the epicenter of the sphere between four and six times larger than the largest yet observed in the United States.

At the distance of 47 km. the anomaly would be from 0.148 to 0.157 dyne, five times the observed value of 0.031. Clearly then the initial interpretation as a sphere, although it satisfies the deflection residuals of the line of traverse, is far from the truth. The mass must have horizontal dimensions much greater than the vertical. Assume for trial that the mass has the form of a vertical cylinder with the same mass and depth to center as the sphere, but of a proportion of height to breadth which shall satisfy approximately the gravity anomaly. The result is shown in the third line of Table XXIX. The gravity anomaly of 0.035 at the epicenter would correspond in a cylinder of these proportions to a value only slightly less at 47 km. But the radius of the cylinder, 200 km., is now far too great. Other cylinders of similar form will, however, give the same anomaly at the epicenter if the depth and dimensions are all divided by any number, n , and the density multiplied by the same number. This gives a series of similar cylinders in which the density varies inversely with the dimensions. Of such a series that shown in the fourth line, obtained by giving n a value of 2, comes fairly close to satisfying all the requirements. The exact degree of adjustment which would be needed to satisfy both the gravity anomaly at 47 km. and the deflections on the line of traverse has not been calculated. If this were done and the dimensions adjusted accordingly, it would complete a second approximation to the real form and mass of No. 2. Such an extended treatment of the subject would, however, be beyond the immediate purposes of this article and beyond the limits of space which it should occupy. The data also are at present hardly of a sort which would justify further computations. It should be emphasized, however, that such a complete investigation is not difficult and would require but little further data, properly chosen, to check the conclusions.

In the first approximation, the mass was assumed to have a uniform distribution about a center, giving a sphere. In the second approximation, the vertical axis is assumed to be different from the horizontal axes, but the latter being kept alike, the horizontal section would still be a circle. A single observation of the gravity anomaly near the epicenter suffices to give this second approximation. The third approximation would be to consider the three

co-ordinate axes of the mass unlike. This would require some observations in two directions at right angles from the epicenter. More complete data consisting of both deflection and gravity observations would of course give still closer approximations toward the real form and depth of the mass. What it is desired to show here, however, is that the interpretation of this large mass as a sphere gave a depth to the center of mass about twice too great and a mass perhaps four times too great. This result is in line with the general deduction previously made in regard to the direction of the error involved in the interpretation of deflection residuals as due to spheres. It contributes its individual testimony to show that the masses producing the notable gravity anomalies and deflection residuals are situated within the zone of isostatic compensation and more especially in the upper part of that zone.

In regard to the large positive mass No. 5 the data are less determinative. At a distance of 60 km. southeast from the epicenter the anomaly is only $+0.005$ dyne. At 150 km. northeast it is -0.027 dyne. It thus appears that there are some large negative masses easterly of No. 5. As this, however, is on the side away from the line of traverse the problem of the real form and mass of No. 5 is at present indeterminate.

The adjustment between the deflection curves due to spherical masses and the values of the deflection residuals has been made closer, perhaps, than the probable values of the residuals. Furthermore, the residuals of Solution G, if they had been given for this region, would have required a somewhat different distribution of masses. A solution for that depth of compensation which would reduce to the smallest quantity the sum of the least squares of the residuals of this area 1,000 km. long and 400 km. wide would be still somewhat different. That local solution which would give the smallest residuals would be such as would make small the algebraic sum of the positive and negative masses, but the difference in mass between positive and negative centers would not be much reduced. The depth to the centers of mass would be the quantity most affected by a change in the hypothesis regarding the depth of compensation. These epicenters then, in so far as the accidental errors do not vitiate the values of the residuals, are realities in nature.

In view of this analysis of the data given in Fig. 12 and in Table XXVIII, it is to be concluded that for this region even the larger outstanding masses from Solution H, capable of exerting a notable influence on the Fx component of the deflections to a distance of 400 km. or more, appear to have their centers not deeper than 20–25 km. Their mass is consequently within the outer half or even the other third of the zone of isostatic compensation as given by Solution H. There is further no evidence of centrospheric heterogeneity.

OTHER INDICATIONS REGARDING DEPTH OF OUTSTANDING MASSES

Deflections by linear or dike-like masses.—The resultants of the deflection residuals are shown by broken lines in Fig. 12. They show a tendency to converge toward centers. This is true in general for the whole United States, as shown in Hayford's illustration. This tendency to convergence indicates that the dominating outstanding masses may usually be regarded in a first or second approximation as symmetrical with respect to a vertical axis. In contrast, however, to this rule the residuals of Solution H in the vicinity of Washington¹ indicate an outstanding mass with a northeast-southwest extension of at least 120 km., whereas the breadth is probably not more than 20 km. This narrowness is shown by the limited distance between the large residuals of opposite sign in a northwest-southeast direction. The linear extension is shown by the parallel rather than radial arrangement of the resultants. The mass gives rise to large deflections for a distance of as great as 100 km. from the sides, but its influence dies out somewhat beyond.

It is clear from these relations that the assumption of a form of the mass symmetrical about a vertical axis for the purpose of determining the depth of the center would not be justifiable. Other assumptions which might be made in order to subject the mass to mathematical investigation would be to consider it as a horizontal prolate spheroid, or as a horizontal linear mass at a certain depth, cylindrical, or as a vertical plate. The latter would be preferable. For a quantitative solution of its dimensions and mass it would be desirable to have some observations farther to the northwest.

¹ Hayford, Supplementary Paper, illustration No. 4.

The following qualitative conclusions may, however, be drawn from an inspection of the residuals.

Maximum deflections are found on each side of the axial line not more than 40 km. distant. The deflections continue large for at least twice this distance but not for three times this distance. The existence of large residuals so close to the axial line shows conclusively that the outstanding mass is within the zone of compensation and apparently within its outer half, but the maintenance of the size of the deflections without much change for a considerably greater distance shows also that it is not merely a surficial and linear mass. It must have considerable extension in depth. In these indications it agrees therefore with the more precise solution of limiting depth given for the Texas-Kansas region.

Indeterminate evidence from anomaly contours.—The map of anomaly contours shown in Fig. 5, Part II, and reduced from Bowie, does not in general throw positive light on the depth of the masses which produce the anomalies of gravity. The necessarily generalized and smoothed-out character of this map has been discussed previously, especially in Part IV. A map based upon more numerous observations would show higher values of maximum anomaly and more of them. The centers of outstanding mass and the anomaly gradients would become better defined, and the distances from epicenter to half value of Fv would average smaller than shown at present. However, notwithstanding the defects, thirty-two measurements were made on this map of the distances from fifteen pronounced maxima to the anomaly contour of half value, and in directions not toward other adjacent maxima. This distance was chiefly controlled therefore by the single dominating mass. The measurements gave an average distance of 120 km.

If the outstanding masses which gave these anomalies were assumed to have the form of spheres, this would give their centers a depth of 160 km. and imply the existence of marked heterogeneity extending below the zone of compensation as given by Solution H. If the average form were assumed, however, to be that oblate mass shown in Fig. 9C, this distance to the contour of half value would correspond to a depth of 100 km. But such assumptions as to form are hypothetical and justifiable only as a step in successive

approximations, not as a conclusion. The anomalies can be accounted for just as readily by an assumption of much shallower depths. The outstanding masses would then possess marked thinness in comparison with their breadth. They would be horizontally extended masses or the algebraic sum of many masses; in either case they could lie within a quarter of the depth indicated by the assumption of spherical form. The mere measurement of the mean distance from epicenter to half value of Fv is therefore wholly indeterminate except as regards the limits of regional compensation. In some respects, however, the present map does give suggestions. Let the attention be turned to these individual features.

A line of stations extends along the margin of the Coastal Plain from Washington, D.C., to Hoboken, New Jersey. The anomalies at the stations and their distances apart as measured on the map are as follows:

- No. 22. Washington, D.C., $+0.039$ dyne
58 km.
- No. 23. Baltimore, Md., -0.011
138 km.
- No. 24. Philadelphia, Pa., $+0.022$
61 km.
- No. 25. Princeton, N.J., -0.019
69 km.
- No. 26. Hoboken, N.J., $+0.024$

This line of stations extends in the direction of the trend of the foundation rocks, yet the sign is reversed at every station, showing marked heterogeneity even in the direction of the strike. The average anomaly without regard to sign is 0.023 , a little larger than the average for the whole United States. The average with respect to sign is $+0.011$. As there is only one station for each of the positive and negative masses the positions and magnitudes of the real maxima and the curves of changing anomaly are unknown. Masses in the upper half of the zone of compensation could produce these effects at these horizontal distances with but little mutual neutralization. Masses below the zone of compensation would, however, have to be very great, not only because the force decreases inversely with the square of the distance, but because masses of opposite sign whose centers are more than 120 km. deep and situated but

from 60 to 70 km. apart would largely neutralize each other in their surface effects. Furthermore, there is no notable extension of the anomaly contours shown in any direction, and more especially at right angles to the line of stations, such as would suggest the wider fields of force due to deep-seated masses. If the masses were at great depth this limitation of attraction to regions near the epicenters could be produced only by a special checkerboard arrangement of opposite masses in all directions. It may be rather firmly concluded, therefore that the anomalies of this chain of stations along a line of low topographic relief are due to heterogeneities of density within the zone of compensation.

In certain regions, as in Florida, in western New York and Pennsylvania, and in the Great Basin, occur broad areas of anomaly showing no central maximum. To some extent this is doubtless due to incompleteness of observations, but in the areas mentioned the stations are so spaced as to show that even if the map were complete there would not exist marked domes of anomaly, such as those central at Minneapolis, Minnesota, and at Lead, South Dakota. This absence of domal form of anomaly curves suggests that the disturbing masses cannot be below the zone of compensation, but should be interpreted as due to the effects of masses widely distributed in the zone of compensation. This relation is especially striking in southern Nevada. The deflection residuals in northern Utah and Nevada all turn away from this southern area of defective mass, shown in Fig. 5, Part II, of this article, as located by Hayford and Bowie. Yet within this broad area of defective mass Station No. 67 shows an anomaly of only -0.013 and some of the surrounding anomalies have actually a larger negative value. There is here then an entire absence of a broad domal form. This is the region which indicates from the least-square equations of the deflections of the vertical the shallowest compensation within the United States; and the combination of the evidence from deflection residuals and anomaly contours goes to show that the anomalies are due to departures from isostasy within that shallow zone.

An inspection of Fig. 5, Part II, shows furthermore that the centers of plus and minus attraction as located by Hayford and Bowie from the deflections of the vertical, although in general

agreement with the measurements of gravity anomalies, so far as the positive or negative sign of the center of mass is concerned, yet are not closely related to the large maxima. They are, in fact, in most cases decidedly eccentric to the anomaly contours. The scarcity of these areas is a result of incompleteness of observations, but their eccentric position and association with areas of moderate anomaly is not an error due to the reconnaissance nature of the studies. These relations indicate that the neighboring regions giving broad domal areas of anomaly are in such cases not due to the dominating control of centrospheric heterogeneity, for in that case the resultants of the deflection residuals would point over broad areas in the general direction of the epicenter of the mass. The degree of discordance between the centers of dominant anomaly and centers of dominant deflection indicates that fuller observations, would produce agreement by adding to the number of such centers. The present data suggest therefore that the areas of broad excess or defect of mass as shown by the anomaly map are due to aggregates more or less composite and shallow, so that each part influences individually to some extent the direction of the deflection residuals about it. Special combinations of masses of shallow depth with other masses below the zone of compensation could, however, also account for the effects. The data of the present map of gravity anomalies are therefore largely indeterminate, but the probabilities point toward at least the greater part of the outstanding masses lying well within the zone of compensation. In this conclusion the data agree with the other lines of evidence.

RELATION OF DEPTH OF OUTSTANDING MASSES TO HYPOTHESES
REGARDING DISTRIBUTION OF COMPENSATION

The measurements of the deflection residuals are very much more detailed than are those of gravity anomalies. The evidence from them is rather conclusive that, for the regions investigated, the excesses or defects of mass which cause those residuals are situated within the zone of compensation and more especially in its outer half or third. Even if centers of outstanding mass were uniformly distributed, however, with respect to depth, they would lose influence in proportion to the square of their depth. Smaller

masses which would exert a very appreciable effect if near the surface would, in consequence, not betray their existence if situated near the base of the zone of compensation. But the larger masses which are found to exist would exert a very visible control upon the deflections of the vertical, even if their centers were at a depth of 100–200 km. The fact that such depths have not been found suggests that the larger variations from the mean density within any one earth shell tend to occur in the outer half of the zone of compensation rather than in its deeper parts or immediately below it.

As a step toward the interpretation of the evidence, let the conclusion reached in Part II of this article be accepted: that regional isostasy for ordinary relief certainly extends to a radius of 100 and probably to 150 or 200 km. Even these limits do not reach the capacity of crustal strength. Such regional limits would not in reality be subject to sharp boundaries. This agrees with the evidence of geology in showing that mountain groups of circum-denudation—those whose relief is due to erosion and not to original differential vertical movement—are upheld by the rigidity of the crust. This applies to many of the mountain groups of the Appalachians; such, for example, as the Catskills.

The fairest initial hypothesis of isostatic compensation would be then to calculate for each station the average elevation of the country within a radius of 99 km., being the outer radius of zone N, and to assume a uniform density to these limits such as is needed to compensate this area. A second trial hypothesis would be to use as the radius of regional compensation the outer limits of zone O, 166.7 km. Under these two calculations for regional compensation the Catskills would be regarded as producing deflections which should show an excess of mass at the surface of the earth. Such an erosion basin as the Nashville basin should show, on the other hand, by its deflections a surface deficiency of mass. For the hypothesis which approaches nearest to the truth, the residuals of the deflections should be small and the outstanding masses would be determined by variations of density within the crust and not of the topography upon its surface.

Under the hypothesis of local compensation as given in Solution H the excess of mass in the Catskills would show, on the contrary,

as a slightly excessive density throughout the whole zone of compensation; the Nashville basin as a slightly deficient density through the same depth. The residuals should indicate an outstanding excess and deficiency of mass respectively with the centers at a depth near the middle of the zone of compensation. But masses with centers at this depth and distance would have a very diminished maximum effect upon the residuals of the deflections of the vertical, and one largely modified by the effects of contiguous regions. Heterogeneities of density nearer the surface and not related to compensation would tend also to overshadow the error involved in the hypothesis of local compensation. It would appear then that the nature of the deflections is not very sensitive for testing the relative probability of the hypotheses of local versus regional compensation. The assistance of a computing office for trying out several hypotheses would probably bring to light, however, conclusions which would be more determinative. These statements must be regarded, therefore, as forecasts not yet subjected to the tests of computation.

In view of the preceding discussion it would seem that the deflection residuals of Solution H are chiefly of value for measuring the heterogeneities of density not related to topography, nor to the mantle of sedimentary rocks. This is especially true of the Texas-Kansas region studied in detail, for there the region is one of plains with an average elevation of about a thousand feet, and the demands of local isostasy as postulated in Solution H would call for a nearly uniform density under all this region. The outstanding masses represent in large part, therefore, real and local variations from a mean density of the continental crust.

But if masses of excess or defect of density similar to those numbered 2 and 5 of Fig. 12 were widely extended, say to a radius of 500 rather than 100 km., they would tend much more strongly to make for a local or intracontinental isostatic adjustment. They would become then not outstanding masses but in large part compensating masses. The outstanding masses represent the same kind of variations, therefore, which if more broadly extended would be in accord with an isostatic adjustment of topography to a different level. They suggest that if the zone of compensation of the continental crust be divided into three shells of 40 km. each in

thickness, the greatest variations in density take place in the outer shell. This conclusion should be regarded as tentative, however, until confirmed by wider detailed studies and more numerous examples.

Accepting for the present this tentative conclusion, how does it agree with that previously reached—that isostatic compensation in some regions appears to go notably deeper than 122 km. and that, where deep, the residuals average smaller than for the continent in general? The answer would appear to be that moderate variations of density are sufficient to account for the isostatic relations of different parts of the continent to each other and that these moderate variations may go very deep.

If the actual distribution of compensation gradually disappears with depth, the hypothesis of uniform compensation complete at a certain depth corresponds to two outstanding masses, one just above the limiting surface, 122 km. in Solution H, the other just below that surface. But these masses would largely balance each other, having opposite signs; so that they would give at the surface of the earth but little evidence of their existence. Imperfections of the hypothesis in regard to the bottom of the zone of compensation would in consequence not readily be detected by methods for determining the depth of outstanding masses.

The isostatic balance of continental crust against oceanic crust is a somewhat different problem from that of the different segments of the continent with respect to each other. Solution H requires a mean difference in specific gravity of about 0.1 to a depth of 122 km. between the crust of the average continental and average oceanic segments. The contrasts in density are therefore pronounced and go very deep. Within the continent, on the other hand, the variations in density related to isostatic compensation are comparatively small and this investigation suggests that those variations may be more largely in the higher levels of the crust.

In conclusion, the depths of the outstanding masses are seen to be related to many problems in crustal statics and dynamics. The depth determines the magnitude of the masses involved and if known will serve as a test of various hypotheses. The excesses and defects of mass departing from that mean which is demanded

by the best hypothesis will be a more accurate measure of the capacity of the rigid crust to carry without viscous yielding loads which have been borne through geologic time, hidden loads whose magnitudes in many regions appear to mask by contrast the present relief between mountains and valleys.

The measure and the meaning of the variable distribution of mass within the lithosphere constitutes an inviting field of geology, discernible in the present, but whose real exploration is a work of the future.

[To be continued]